

# Chromo-polarizability and $\pi\pi$ final state interaction

Feng-Kun Guo,<sup>1,2,6</sup> Peng-Nian Shen,<sup>2,1,4,5</sup> and Huan-Ching Chiang<sup>3,1,5</sup>

<sup>1</sup>*Institute of High Energy Physics, Chinese Academy of Sciences, P.O.Box 918(4), Beijing 100049, China*

<sup>2</sup>*CCAST(World Lab.), P.O.Box 8730, Beijing 100080, China*

<sup>3</sup>*South-West University, Chongqing 400715, China*

<sup>4</sup>*Institute of Theoretical Physics, Chinese Academy of Sciences, P.O.Box 2735, China*

<sup>5</sup>*Center of Theoretical Nuclear Physics, National Laboratory of Heavy Ion Accelerator, Lanzhou 730000, China*

<sup>6</sup>*Graduate University of Chinese Academy of Sciences, Beijing 100049, China*

(Dated: June 23, 2006)

The chromo-polarizability of a quarkonium state is a measure of the amplitude of the  $E1$ - $E1$  chromo-electric interaction of the quarkonium with soft gluon fields and can be measured in the heavy quarkonium decays. Based on the chiral unitary approach, formulas with modification caused by the  $S$  wave  $\pi\pi$  final state interaction (FSI) for measuring the chromo-polarizabilities are given. It is shown that the effect of the  $S$  wave  $\pi\pi$  FSI is very important in extracting chromo-polarizabilities from the experimental data. The resultant values with the FSI are reduced to about 1/3 of those determined without the FSI. The consequences of the FSI correction in the  $J/\psi$ -nucleon scattering near the threshold are also discussed. The estimated lower bound of the total cross section is reduced from about 17 mb to 2.9 mb, which agrees with the experimental data point and is compatible with the previously estimated values in the literature. In order to understand the interaction of heavy quarkonia with light hadrons at low energies better and to obtain the chromo-polarizabilities of quarkonia accurately, more data should be accumulated. This can be done in the  $J/\psi \rightarrow \pi^+\pi^-l^+l^-$  decay at BES-III and CLEO-c and in the  $\Upsilon \rightarrow \pi^+\pi^-l^+l^-$  decay at B factories.

PACS numbers: 13.25.Gv, 12.38.-t, 13.75.Lb, 14.40.Gx

Keywords: chromo-polarizability,  $\pi\pi$  final state interaction,  $J/\psi$ -nucleon scattering

It was proposed that the suppression of the  $J/\psi$  production could be regarded as a signature for the formation of a quark-gluon plasma (QGP) due to the color screening [1]. The interaction of  $J/\psi$  with light hadrons is very important in studying the  $J/\psi$  suppression in heavy ion collision and in obtaining an unambiguous signal of the QGP [2]. Many studies on this subject have been done by using various methods and broad ranges of theoretical predictions have been resulted, for a review, see Ref. [2].

Recently, Sibirtsev and Voloshin studied [3] the interaction of  $J/\psi$  and  $\psi'$  with nucleons at low energies near threshold by employing the multipole expansion method [4, 5] and low-energy theorems in QCD [6]. They argued that the total cross section of the  $J/\psi$ -nucleon elastic scattering at the threshold is very likely to be larger than 17 mb which is significantly larger than the previously estimated values in the literature. Their result supports the existence of possible bound light  $J/\psi$ -nucleus states. Comparing with the experimental value of  $\sigma_{J/\psi N} = 3.8 \pm 0.8 \pm 0.5$  mb at  $\sqrt{s} \approx 5.7$  GeV [7], the large cross section value given in Ref. [3] suggested a noticeable rise towards the threshold. It should be mentioned that such a result is based on the chromo-polarizability  $\alpha_{J/\psi}$  which appears in describing the interaction of  $J/\psi$  with soft gluons. However, this value is unknown so far. Although a value of  $2 \text{ GeV}^{-3}$  of  $|\alpha_{\psi' J/\psi}|$  was used as a reference, it was argued that the actual value could be somewhat larger. The value of  $|\alpha_{\psi' J/\psi}|$  was estimated by Voloshin via the  $\psi' \rightarrow J/\psi \pi^+ \pi^-$  decay process by using the QCD multipole expansion method [8].

The low energy interaction of a heavy quarkonium with a light hadron is mediated by soft gluons. The heavy quarkonium has a small size comparing with the wavelengths of gluons, so that one can use a multipole expansion to study the heavy quarkonium interaction with a soft gluon [4, 5]. The leading  $E1$  chromo-electric dipole term in the expansion is simply  $H_{E1} = -\frac{1}{2}\xi^a \vec{r} \cdot \vec{E}^a(0)$  [4, 5], where  $\xi^a$  is the difference between the color generators acting on the quark and anti-quark, respectively, and can be expressed as  $\xi^a = t_1^a - t_2^a$  with  $t_i^a = \lambda_i^a/2$  and  $\lambda_i^a$  being Gell-Mann matrices.  $\vec{r}$  is the coordinate of the relative position between the quark and anti-quark. The QCD coupling constant  $g$  is included in the definition of the normalized gluon field. Using the notations in Ref. [3], the lowest order amplitude of the transition between two  $^3S_1$  heavy quarkonium states  $A$  and  $B$  with an emitted gluon system which possesses the quantum numbers of the dipion is in the second order of  $H_{E1}$

$$\langle B | H_{eff} | A \rangle = -\frac{1}{2} \alpha_{AB} \vec{E}^a \cdot \vec{E}^a, \quad (1)$$

where the nonrelativistic normalization is used for the quarkonium states.  $\alpha_{AB}$  is the chromo-polarizability which is a measure of the amplitude of the  $E1$ - $E1$  chromo-electric interaction of the quarkonium with soft gluon fields and is related to the Green's function  $G_A$  for a heavy quark pair in the color-octet state.

The amplitude for the  $\pi^+\pi^-$  transition between  $A$  and  $B$  can be written as

$$T_{AB} = 2\sqrt{M_A M_B} \alpha_{AB} \langle \pi^+ \pi^- | \frac{1}{2} \vec{E}^a \cdot \vec{E}^a | 0 \rangle, \quad (2)$$

where the factor  $2\sqrt{M_A M_B}$  appears due to the relativistic normalization of the decay amplitude  $T_{AB}$ . It was pointed out that the dominant part of the two-pion production amplitude by the gluonic operator  $\vec{E}^a \cdot \vec{E}^a$  can be determined by the trace anomaly and chiral algebra [6]

$$\begin{aligned} \langle \pi^+ \pi^- | \vec{E}^a \cdot \vec{E}^a | 0 \rangle &= \frac{8\pi^2}{b} q^2 + O(\alpha_s q_0^2) + O(m_\pi^2) \\ &\approx \frac{8\pi^2}{b} (q^2 - C), \end{aligned} \quad (3)$$

where  $q$  is the total four-momentum of the produced dipion system,  $q_0$  is the total energy of the system,  $b = 9$  is the first coefficient in the QCD  $\beta$  function with three light flavors, and  $C$  is a constant to evaluate approximately the contributions of sub-leading terms [8, 11] which vary relatively slow with  $q^2$  in the physical region of the pionic transitions [12]. Theoretically, the chromo-polarizability is, at least, highly model-dependent [8] in the present stage. Therefore, it would be nice if the values of  $\alpha_{AB}$  could be extracted from experimental data. Voloshin performed such an analysis [8] and gave the estimations of  $|\alpha_{\psi' J/\psi}| \approx 2.0 \text{ GeV}^{-3}$  and  $|\alpha_{\Upsilon' \Upsilon}| \approx 0.66 \text{ GeV}^{-3}$ . In the same reference, it was also suggested that the chromo-polarizabilities of  $J/\psi$  and  $\Upsilon$  can directly be measured in the decays  $J/\psi \rightarrow \pi^+ \pi^- l^+ l^-$  and  $\Upsilon \rightarrow \pi^+ \pi^- l^+ l^-$  with soft pions. Based on an approximation that the intermediate state to the lepton pairs is the  $1^3 S_1$  quarkonium state itself, the diagonal polarizabilities (i.e.  $\alpha_{AA}$ , written as  $\alpha_A$  for simplicity) of  $J/\psi$  and  $\Upsilon$  can be written as [8]

$$\begin{aligned} d\Gamma(1^3 S_1 \rightarrow \pi^+ \pi^- l^+ l^-) &= \frac{(q^2 - C)^2}{4b^2 q_0^2} |\alpha_{1S}|^2 \sqrt{1 - \frac{4m_\pi^2}{q^2}} \\ &\times \sqrt{q_0^2 - q^2} \Gamma_{ee}(1^3 S_1) dq^2 dq_0, \end{aligned} \quad (4)$$

where  $\Gamma_{ee}(1^3 S_1) \equiv \Gamma(1^3 S_1 \rightarrow l^+ l^-)$  is the leptonic width of the  $1^3 S_1$  state.

On the other hand, the  $S$  wave  $\pi\pi$  FSI plays an important role in the heavy quarkonium  $\pi^+ \pi^-$  transitions [9, 10]. This FSI would modify the  $\pi^+ \pi^-$  production amplitude and consequently would change the determined chromo-polarizabilities. There are various ways to account for the  $S$  wave  $\pi\pi$  FSI. One of the efficient methods

is the coupled-channel chiral unitary approach (ChUA) [13].

By employing such an approach, the  $S$  wave  $\pi\pi$  phase shift data can be well described with one parameter, a 3-momentum cut-off  $q_{max} = 1.03 \text{ GeV}$ , only, and the low-lying scalar mesons ( $\sigma$ ,  $f_0(980)$ ,  $a_0(980)$  and  $\kappa$ ) with reasonable masses and widths can dynamically be generated [13, 14]. For the  $S$  wave isoscalar channel, the  $\pi\pi$  and  $K\bar{K}$  channels are taken into account (for detailed information, refer to Ref. [13]). The normalizations used are  $\langle \pi^+ \pi^- | \pi^+ \pi^- \rangle = \langle \pi^- \pi^+ | \pi^- \pi^+ \rangle = \langle \pi^0 \pi^0 | \pi^0 \pi^0 \rangle = 2$  and  $|\pi\pi\rangle^{I=0} = (|\pi^+ \pi^- + \pi^- \pi^+ + \pi^0 \pi^0\rangle)/\sqrt{6}$ . Thus the full amplitude of the process  $\pi^+ \pi^- + \pi^- \pi^+ + \pi^0 \pi^0 \rightarrow \pi^+ \pi^-$  can be expressed as

$$\langle \pi^+ \pi^- | T | \pi^+ \pi^- + \pi^- \pi^+ + \pi^0 \pi^0 \rangle = 2T_{\pi\pi, \pi\pi}^{I=0}, \quad (5)$$

where  $T_{\pi\pi, \pi\pi}^{I=0}$  is the full  $S$  wave  $\pi\pi \rightarrow \pi\pi$  coupled-channel amplitude for  $I = 0$ . Note that the  $K\bar{K}$  channel appears in the intermediate states [13].

By considering the  $S$  wave  $\pi\pi$  FSI by ChUA [10, 15, 16], the decay amplitude of the  $A \rightarrow B\pi^+ \pi^-$  process is modified to

$$T_{AB} = \frac{8\pi^2}{b} \sqrt{M_A M_B} \alpha_{AB} (q^2 - C) (1 + 2G_\pi(q^2) T_{\pi\pi, \pi\pi}^{I=0}(q^2)), \quad (6)$$

where  $G_\pi(q^2)$  is the two-pion loop integral

$$G_\pi(q^2) = i \int \frac{d^4 q}{(2\pi)^4} \frac{1}{q^2 - m_\pi^2 + i\varepsilon} \frac{1}{(p' - p - q)^2 - m_\pi^2 + i\varepsilon}, \quad (7)$$

where  $p'$  and  $p$  represent the momenta of the initial and the final quarkonium states, respectively. The loop integration can be calculated with the same cut-off momentum,  $q_{max} = 1.03 \text{ GeV}$ , as the one used in describing the  $S$  wave  $\pi\pi$  scattering data [13]. In this way, the consistency between the used  $\pi\pi$  FSI and the  $\pi\pi$  scattering is guaranteed. Note that the direct  $\pi\pi$  production amplitude in Eq. (3) is independent of the momentum carried by one of the produced pion, i.e. the integrated loop momentum, hence can be factorized out from the loop integral. According to Refs. [13, 17, 18], the amplitude  $T_{\pi\pi, \pi\pi}^{I=0}$  in Eq. (6) can be factorized out from the loop integral.

Now, in terms of Eq. (6), one can easily work out the differential width for the  $A \rightarrow B\pi^+ \pi^-$  decay

$$d\Gamma(A \rightarrow B\pi^+ \pi^-) = \frac{2\pi M_B}{b^2 M_A} |\alpha_{AB}|^2 (q^2 - C)^2 |1 + 2G_\pi(q^2) T_{\pi\pi, \pi\pi}^{I=0}(q^2)|^2 \sqrt{\frac{q^2}{4} - m_\pi^2} q_B dm_{\pi\pi}, \quad (8)$$

where the polarizations of particle  $A$  are averaged, and

the polarizations of particle  $B$  are summed, and  $q_B$  is the

magnitude of the 3-momentum of the  $B$  state in the rest frame of particle  $A$

$$q_B = \frac{1}{2M_A} \sqrt{(M_A^2 - (m_{\pi\pi} + M_B)^2)(M_A^2 - (m_{\pi\pi} - M_B)^2)}. \quad (9)$$

To demonstrate the effect of the  $\pi\pi$  FSI on the differential width, we plot the factor  $|1 + 2G_\pi(q^2)T_{\pi\pi,\pi\pi}^{I=0}(q^2)|$  versus the invariant mass of  $\pi^+\pi^-$ ,  $m_{\pi\pi} = \sqrt{q^2}$ , in Fig. 1. From the figure, one sees that around  $m_{\pi\pi} = 0.48$  GeV, this factor could be enhanced up to 2.8 from unity by the FSI.

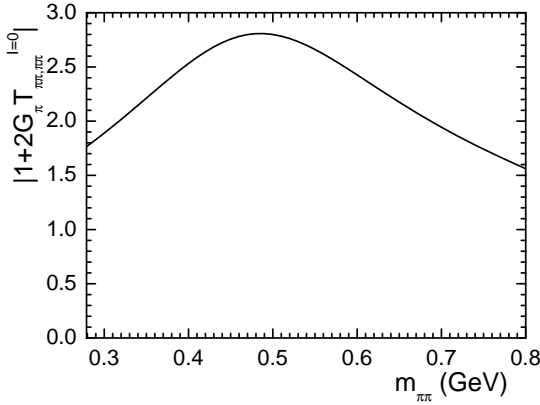


FIG. 1:  $|1 + 2G_\pi(q^2)T_{\pi\pi,\pi\pi}^{I=0}(q^2)|$  as a function of the invariant mass of  $\pi^+\pi^-$ .

In order to determine the transition chromopolarizabilities  $\alpha_{\psi' J/\psi}$  and  $\alpha_{\Upsilon' \Upsilon}$ , we fit the theoretical results to the experimental  $\pi^+\pi^-$  invariant mass spectra from the BES  $\psi' \rightarrow J/\psi \pi^+\pi^-$  decay data [19] and the CLEO  $\Upsilon' \rightarrow \Upsilon \pi^+\pi^-$  decay data [20], and the corresponding decay widths  $\Gamma(\psi' \rightarrow J/\psi \pi^+\pi^-) = 715.8$  keV and  $\Gamma(\Upsilon' \rightarrow \Upsilon \pi^+\pi^-) = 8.08$  keV [21] by adjusting  $C$  and  $\alpha_{AB}$  in Eq. (8) as free parameters. The fitted  $\pi^+\pi^-$  invariant spectra for  $\psi' \rightarrow J/\psi \pi^+\pi^-$  and  $\Upsilon' \rightarrow \Upsilon \pi^+\pi^-$  decays are plotted in Fig. 2 and Fig. 3, respectively. In these figures, the solid and dashed curves represent the results with and without the  $S$  wave  $\pi\pi$  FSI, respectively. The resultant parameters through the best fitting are listed in Table I. It is shown that the  $S$  wave  $\pi\pi$  FSI provides rather large modifications to the values of  $|\alpha_{\psi' J/\psi}|$  and  $|\alpha_{\Upsilon' \Upsilon}|$ . The resultant values with the  $\pi\pi$  FSI are almost 1/3 of the those without the  $\pi\pi$  FSI. It should be emphasized that such a modification is meaningful, because no more free parameters are adopted when the  $\pi\pi$  FSI is included. It should also be mentioned that the parameter values obtained in the without FSI case are slightly different with those given by Voloshin, because some approximations was made in the width formula in Ref. [8].

In the same way, Eq. (4) for determining diagonal polarizability  $\alpha_{1S}$  should also be modified by multiplying

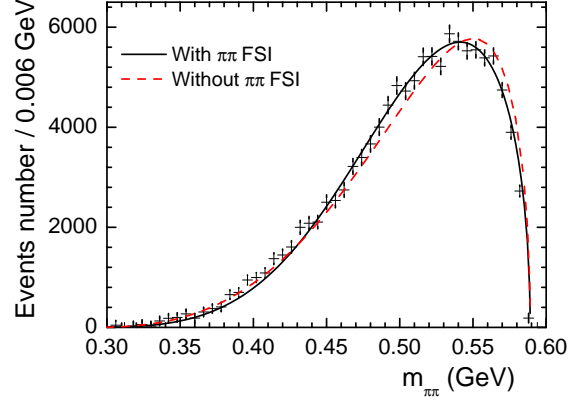


FIG. 2: The  $\pi^+\pi^-$  invariant mass spectrum for the  $\psi' \rightarrow J/\psi \pi^+\pi^-$  decay. The solid and dashed curves are calculated in the with  $\pi\pi$  FSI and without  $\pi\pi$  FSI cases, respectively.

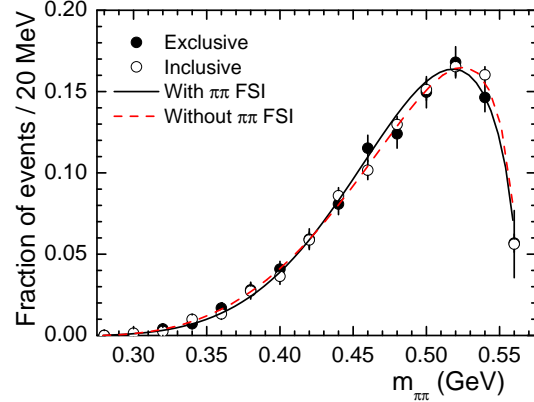


FIG. 3: The  $\pi^+\pi^-$  invariant mass spectrum for the decay  $\Upsilon' \rightarrow \Upsilon \pi^+\pi^-$ . The solid and dashed curves are calculated in the with  $\pi\pi$  FSI and without  $\pi\pi$  FSI cases, respectively.

the FSI factor  $|1 + 2G_\pi(q^2)T_{\pi\pi,\pi\pi}^{I=0}(q^2)|^2$ , namely,

TABLE I: Parameters used in the heavy quarkonium  $\pi^+\pi^-$  transitions with and without the  $\pi\pi$  FSI.

	Without $\pi\pi$ FSI	With $\pi\pi$ FSI
$ \alpha_{\psi' J/\psi} $ ( $\text{GeV}^{-3}$ )	$2.24 \pm 0.02$	$0.83 \pm 0.01$
$ \alpha_{\Upsilon' \Upsilon} $ ( $\text{GeV}^{-3}$ )	$0.70 \pm 0.01$	$0.24 \pm 0.01$
$C_{\psi' \rightarrow J/\psi \pi^+\pi^-}$ ( $m_\pi^2$ )	$4.27 \pm 0.07$	$4.25 \pm 0.09$
$C_{\Upsilon' \rightarrow \Upsilon \pi^+\pi^-}$ ( $m_\pi^2$ )	$3.45 \pm 0.15$	$2.86 \pm 0.21$

$$d\Gamma(1^3S_1 \rightarrow \pi^+\pi^-l^+l^-) = \frac{(q^2 - C)^2}{4b^2q_0^2} |1 + 2G_\pi(q^2)T_{\pi\pi,\pi\pi}^{I=0}(q^2)|^2 |\alpha_{1S}|^2 \sqrt{1 - \frac{4m_\pi^2}{q^2}} \sqrt{q_0^2 - q^2} \Gamma_{ee}(1^3S_1) dq^2 dq_0. \quad (10)$$

It was shown [8] that by restricting the maximal value of  $q_0$  (or a lower cut-off on the invariant mass of the lepton pair) to about 0.9 GeV, the higher intermediate state effect comes from the  $2S$  state only and can be evaluated through the experimental data analysis by using Eq.(13) in Ref. [8] without additional parameters (except for an overall phase).

Now we are able to investigate the effects of the  $\pi\pi$  FSI corrected  $|\alpha_{\psi'J/\psi}|$  on the scattering quantities in the  $J/\psi$ -nucleon scattering. The  $J/\psi$ -nucleon total cross section was measured as  $\sigma_{J/\psi N} = 3.8 \pm 0.8 \pm 0.5$  mb at  $\sqrt{s} \approx 5.7$  GeV [7]. There are also some theoretical calculations (see review of this subject in Ref. [23]). For instance, Brodsky and Miller demonstrated the fact that the two-gluons exchange in the scalar channel dominates the elastic  $J/\psi$ -nucleon scattering and obtained  $\sigma_{J/\psi N} \approx 7$  mb at threshold [24]. Based on the operator product expansion and the trace anomaly, Teramond et al. found that the total cross section at threshold is about 5 mb [25]. In general, the range of predicted elastic  $J/\psi + N \rightarrow J/\psi + N$  cross section at  $p_{J/\psi} \approx 0$  GeV is  $1.25 \sim 5$  mb [23]. Recently, in terms of the multipole expansion and the low energy theorem, Sibirtsev and Voloshin showed the lower bound of the total cross section at the threshold is about 17 mb [3].

It is known that the amplitude of the  $J/\psi$ -nucleon scattering at low energies is proportional to the chromo-polarizability of  $J/\psi$ ,  $\alpha_{J/\psi}$  [3],

$$T_{J/\psi N} = \frac{16\pi^2}{9}(1 + D)\alpha_{J/\psi}M_{J/\psi}m_N^2, \quad (11)$$

where  $D \geq 1$  is a constant. Consequently, the scattering length and the total cross section are proportional to  $\alpha_{J/\psi}$  and  $\alpha_{J/\psi}^2$ , respectively. The in-medium mass shift of  $J/\psi$  is equal to the real part of the potential [3, 22], and hence is also proportional to  $\alpha_{J/\psi}$ . We present the estimated values of the scattering length  $a_{J/\psi}$ , the cross section near the threshold  $\sigma_{J/\psi N}$  and the  $J/\psi$  mass shift  $\Delta M_{J/\psi}$  in Table II. In the calculation,  $\alpha_{J/\psi} = 0.83$  GeV $^{-3}$  in the with  $S$  wave  $\pi\pi$  FSI case and  $\alpha_{J/\psi} = 2$  GeV $^{-3}$  in the without  $S$  wave  $\pi\pi$  FSI case [3], respectively.

It should be noted that similar to those in Ref. [3], all of the estimated results in Table II are just the lower bounds, because the lower bound values of  $\alpha_{J/\psi}$  and  $D$  are used. Thus, the estimated cross section of  $J/\psi$ -nucleon scattering near threshold in Ref. [3] is reduced from  $\gtrsim 17$  mb to  $\gtrsim 2.9$  mb. Unlike that in Ref. [3], this lower bound value agrees with the experimental value of

TABLE II: Scattering length, cross sections and  $J/\psi$  mass shift ( $\alpha_{J/\psi} = 0.83$  GeV $^{-3}$  in the with  $S$  wave  $\pi\pi$  FSI case and  $\alpha_{J/\psi} = 2$  GeV $^{-3}$  in the without  $S$  wave  $\pi\pi$  FSI case [3]).

	Without $\pi\pi$ FSI [3]	With $\pi\pi$ FSI
$a_{J/\psi}$ (fm)	0.37	0.15
$\sigma_{J/\psi N}$ (mb)	17	2.9
$-\Delta M_{J/\psi}$ (MeV)	21	8.7

$\sigma_{J/\psi N} = 3.8 \pm 0.8 \pm 0.5$  mb at  $\sqrt{s} \approx 5.7$  GeV [7] and compatible with the theoretical results in Refs. [23, 24, 25].

In conclusion, the effect of the  $S$  wave  $\pi\pi$  FSI on determining the chromo-polarizability is studied. The FSI corrected formula for analyzing  $J/\psi$  and  $\Upsilon$   $\pi^+\pi^-$  transition data to get the chromo-polarizabilities of  $J/\psi$  and  $\Upsilon$  is given. It is found that the effect of the  $\pi\pi$  FSI is quite sizeable, so that the values of chromo-polarizabilities  $|\alpha_{\psi'J/\psi}|$  and  $|\alpha_{\Upsilon'\Upsilon}|$  can be reduced to about 1/3 of those in the without  $\pi\pi$  FSI case. As a consequence, the scattering length and the in-medium mass shift of  $J/\psi$  are reduced to about 5/12 of the values given in Ref. [3] where  $|\alpha_{\psi'J/\psi}| = 2$  GeV $^{-3}$  was employed [8], and the estimated lower bound of the total cross section is reduced from 17 mb [3] to 2.9 mb. We suggest that in terms of Eq. (10),  $\alpha_{J/\psi}$  should be further measured in the  $J/\psi \rightarrow \pi^+\pi^-l^+l^-$  decay at CLEO-c and future BES-III, and  $|\alpha_{\Upsilon'\Upsilon}|$  should be further investigated in the  $\Upsilon \rightarrow \pi^+\pi^-l^+l^-$  decay in B factories. The precisely measured values would be very important in studying the scattering of  $J/\psi$  ( $\Upsilon$ ) with light hadrons, and hence in understanding the  $J/\psi$  suppression in heavy-ion collisions.

This work is partially supported by the NSFC grant Nos. 10475089, 10435080, CAS Knowledge Innovation Key-Project grant No. KJCX2SWN02 and Key Knowledge Innovation Project of IHEP, CAS (U529).

- 
- [1] T. Matsui and H. Satz, Phys. Lett. B **178**, 416 (1986).
  - [2] T. Barnes, at the Conference on Quarks and Nuclear Physics (QNP2002), June 2002, Jülich, Germany [arXiv: nucl-th/0306031].
  - [3] A. Sibirtsev and M.B. Voloshin, Phys. Rev. D **71**, 076005 (2005).
  - [4] K. Gottfried, Phys. Rev. Lett. **40**, 598 (1978).
  - [5] M.B. Voloshin, Nucl. Phys. **B154**, 365 (1979).
  - [6] M. Voloshin and V. Zakharov, Phys. Rev. Lett. **45**, 688

- (1980).
- [7] R.L. Anderson *et al.*, Phys. Rev. Lett. **38**, 263 (1977).
  - [8] M.B. Voloshin, Mod. Phys. Lett. A **19**, 665 (2004).
  - [9] T.A. Lähde, D.O. Riska, Nucl. Phys. **A707**, 425 (2002).
  - [10] F.-K. Guo, P.-N. Shen, H.-C. Chiang, and R.-G. Ping, Nucl. Phys. **A761**, 269 (2005).
  - [11] M.B. Voloshin and V.I. Zakharov, Sov. Phys. Usp. **30**, 553 (1987) [Usp. Fiz. Nauk **152**, 361 (1987)].
  - [12] V.A. Novikov and M.A. Shifman, Z. Phys. C **8**, 43 (1981).
  - [13] J.A. Oller and E. Oset, Nucl. Phys. **A620**, 438 (1997); (Erratum) *ibid.* **A652**, 407 (1999).
  - [14] F.-K. Guo, R.-G. Ping, P.-N. Shen, H.-C. Chiang, and B.-S. Zou, accepted for publication in Nucl. Phys. A [arXiv: hep-ph/0509050].
  - [15] J.A. Oller and E. Oset, Nucl. Phys. **A629**, 739 (1998).
  - [16] Ulf-G. Meißner and J.A. Oller, Nucl. Phys. **A679**, 671 (2001).
  - [17] J.A. Oller and E. Oset, Phys. Rev. D **60**, 074023 (1999).
  - [18] J. Nieves and E. Ruiz Arriola, Nucl. Phys. **A679**, 57 (2000).
  - [19] BES Collaboration, J.Z. Bai *et al.*, Phys. Rev. D **62**, 032002 (2000).
  - [20] CLEO Collaboration, J.P. Alexander *et al.*, Phys. Rev. D **58**, 052004 (1998).
  - [21] Particle Data Group, S. Eidelman *et al.*, Phys. Lett. B **592**, 1 (2004).
  - [22] A. Hayashigaki, Prog. Theor. Phys. **101**, 923 (1999).
  - [23] A. Sibirtsev, K. Tsushima, and A.W. Thomas, Phys. Rev. C **63**, 044906 (2001).
  - [24] S.J. Brodsky and G.A. Miller, Phys. Lett. B **412**, 125 (1997).
  - [25] G.F. de Teramond, R. Espinoza, and M. Ortega-Rodriguez, Phys. Rev. D **58**, 034012 (1998).